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Design of two PM Synchronous Machines for EV Traction Using Open-Source Design Instruments

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***Abstract*— This preliminary paper presents a design procedure for Permanent-magnet synchronous motors (PMSMs) targeting one PM-assisted synchronous reluctance (PMASyR) motor and one surface mounted PM motor with concentrated windings (CW-SPM) for EV application. The design process takes advantage of a combination of design equations, finite element analysis (FEA) and multi-objective optimization. EV application was chosen for its many challenging aspects, including magnetic and multi-physical modelling. Thermal and structural aspects are also included in the study. The preliminary results presented in this short paper are the efficiency maps and the limits of operation in the torque and speed domain of the two motor designs, and the comparison with selected benchmark designs.**

***Index Terms*—Permanent-magnet motor, Traction motor drives, Automatic design, Finite element analysis, Open-Source.**

I. Introduction

This study addresses a complete design procedure of Permanent-magnet Synchronous motors (PMSMs) implemented in open-source design software. The design software [1] embeds parametric sizing equations, optimization algorithms and finite element analysis [2].

PMSMs are custom designed for each application, and the electric vehicle (EV) traction drive is a challenging application design case, including a multitude of transient operating points, also varying quite substantially after the different driving cycles. Among PMSMs, the ones applied to EVs are the concentrated-winding surfaced-mounted PM (CW-SPM) machine and the interior PM (IPM) machine, for their torque density and efficiency, and extended speed range [3]. PM-assisted Synchronous Reluctance (PMASyR) motors are a class of IPM machines appropriate for EV traction, for their superior high-speed efficiency and for potential replacement of rare earth PM materials with cheaper ferrite PMs [4]-[5].

Design optimization of PMSMs was thoroughly investigated in the literature [6]. Automatic design based on optimization algorithms was investigated in previous work [7], even if limited to specific design aspects. The traction motors presented in [5] are used here as a benchmark to design two new electrical machines by means of the open-source procedure: one CW-SPM and one PM-SyR. FEA calculated efficiency maps are presented as the preliminary results of the analysis, for the two new designs.

II. Design Procedure

The main geometry and the power converter ratings are common to all designs: benchmark motors and new motors presented here. The ratings of the motors are shown in table I.

TABLE I - Parameters of the automatic designed motors and benchmark motors

		PMASR		CW-SPM	
		[5]	present	[5]	present
COMMON SPECS					
Power at max. speed	W	50000			
Maximum speed	rpm	12000			
Base speed	rpm	4000			
Torque at base speed	Nm	110			
Converter Voltage	V	173			
Converter Current	A pk	360			
Pole pairs		2			
Stator slots		48		6	
Stator outer diameter	mm	216			
Stator bore diameter	mm	142		124	
Stack length	mm	170			
Airgap	mm	0.7		0.7	
Copper fill factor		0.4		0.4	
Steel grade		M250-35A			
PM grade		BMN-42SH			
Target Rotor temp.	°C	150			
Target Copper temp.	°C	130			
OTHER DATA					
Number of turns		20	24	23	
Torque @ 360 A	Nm	210	240	150	164
Characteristic current	A pk	205	206	193	249
Stator resistance	Ω	0.027	0.023	0.026	0.016

A. Design Flowchart

The design flowchart is reported in Fig. 1 for the PMASyR design. Preliminary design equations are by the book [8]. The key input defining the approach is that electric loading is expressed in the form of copper loss per outer stack surface (factor k_j (W/m^2) in Fig. 1). The two goals of this first design step are torque maximization and high-speed power requirement, obtained by design of the characteristic current of each machine. After analytical sizing, the designs withstand a preliminary FEA identification to assess if torque and characteristic current targets are met. If necessary, the initial design is iterated. Additional references for design equations are [9] for the PMA-SyR machine, and [10] for the CW-SPM machine. After this stage is completed, the designs are comprehensively FEA evaluated in terms of torque, flux maps, iron and PM loss maps. FEA maps are off-line processed to obtain [11]. Besides the magnetics, structural and thermal issues are also accounted for. The final paper will provide full details of the design equations and procedure, for both the considered machine types.

B. Multi-Objective Optimization

Single design aspects can be targeted for optimization using multi-objective differential evolution (MODE) and FEA, at any stage of the design pipeline. In theory, the design could be fully automatic, delegated to the MODE process, but this is not recommendable and can be avoided by appropriate use of the sizing equations, embedded into [1]. For example, optimization parameters for the CW-SPM design could be tooth length, tooth width, slot opening, rotor diameter and PM thickness, and design goals could include torque, torque ripple and target characteristic current. One example MODE run took 3600 FEA evaluations of candidate designs, resulting in a Pareto front, from where a final design was selected. This takes approximately 8 hours. If, otherwise, MODE is applied to torque ripple optimization of an already designed machine, the optimization refinement takes only 2.5 hours. Comparative results will be provided in the final paper. The final structure of both PMASyR and CW-SPM motors are shown in Fig. 2.

III. Preliminary Results: Efficiency Maps

The efficiency maps are reported in Fig. 3 for the two machine designs, according to the specifications in Table I. The efficiency of the two motors is better than those of corresponding benchmarks [5].

A. FEA Evaluation of Loss and Efficiency

Core, PM, and copper losses of the motors are FEA evaluated (2D), current control and constant speed conditions (3500 rpm). Simulations are repeated over the machine current domain get to complete loss characterization at constant speed. Off-line association of loss values to each speed (frequency) and torque operating point follows the procedure in [11].

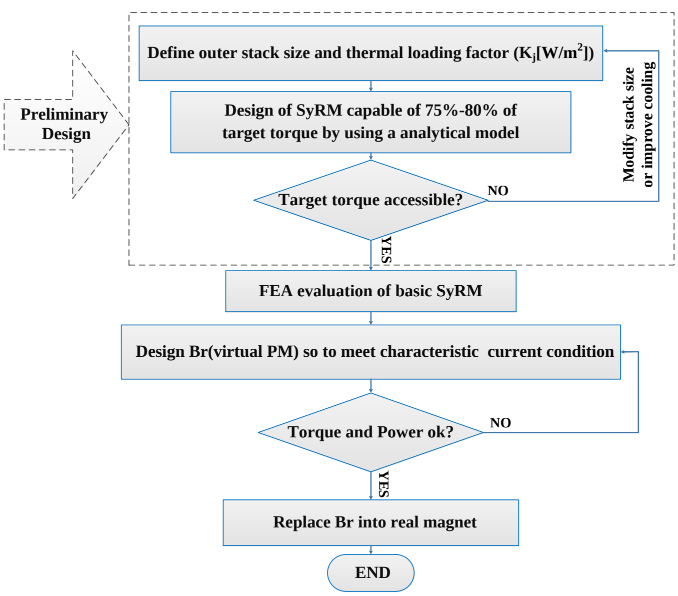

Fig.1. Design Flowchart used for the PMASyR machine

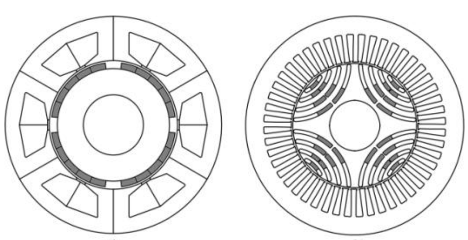

Fig.2. Final designs: a) CW-SPM motor; b) PMASyR motor.

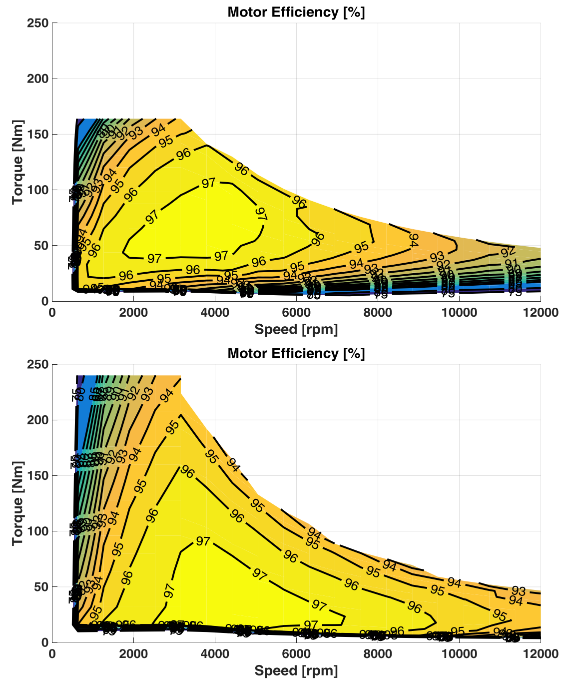

Fig.3. Efficiency map, (a) CW-SPM motor, (b) PMASyR motor

The full paper will provide a comprehensive assessment of magnetic and non-magnetic aspects (risk of demagnetization, segregation of harmonic loss, effect of PM segmentation, centrifugal stress, copper and PM temperature verification).

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